Foundation of Cryptography (0368-4162-01), Lecture 7

MACs and Signatures

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Section 1

Message Authentication Code (MAC)

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Definition 1 (MAC)

A trippet of PPT's $(\mathsf{Gen}, \mathsf{Mac}, \mathsf{Vrfy})$ such that

1. $\mathsf{Gen}(1^n)$ outputs a key $k \in \{0,1\}^*$
2. $\mathsf{Mac}(k, m)$ outputs a “tag" t
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Consistency: $\mathsf{Vrfy}_k(m, t) = 1$ for any $k \in \mathsf{Supp}(\mathsf{Gen}(1^n))$, $m \in \{0,1\}^n$ and $t = \mathsf{Mac}_k(m)$

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Definition 2 (Existential unforgability)

A MAC $(\mathsf{Gen}, \mathsf{Mac}, \mathsf{Vrfy})$ is existential unforgeable (EU), if for any oracle-aided PPT A:

$$\Pr\Big[k \leftarrow \mathsf{Gen}(1^n); (m, t) \leftarrow \mathsf{A}^{\mathsf{Mac}_k, \mathsf{Vrfy}_k}(1^n): \\ \mathsf{Vrfy}_k(m, t) = 1 \wedge \mathsf{Mac}_k \text{ was not asked on } m\Big] = \mathsf{neg}(n)$$

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Length-restricted MACs

Definition 3 (Length-restricted MAC)

Same as in Definition 1, but for $k \in \mathrm{Supp}(G(1^n))$, Mac_k and Vrfy_k only accept messages of length n.

Bounded-query MACs

Definition 4 (ℓ-time MAC)

A MAC scheme is existential unforgeable against ℓ queries (for short, ℓ-time MAC), if it is existential unforgeable as in Definition 2, but A can only ask for ℓ queries.

Section 2

Constructions

Zero-time, restricted length, MAC

Construction 5 (Zero-time, restricted length, MAC)

- $\mathsf{Gen}(1^n)$: outputs $k \leftarrow \{0,1\}^n$
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- $\mathsf{Vrfy}_k(m,t) = 1$, iff $t = k$

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Claim 6

The above scheme is a length-restricted, zero-time MAC

ℓ-wise independent hash

Definition 7 (ℓ-wise independent)

A function family $\mathcal{H}$ from $\{0,1\}^n$ to $\{0,1\}^m$ is ℓ-wise independent, where $\ell \in \mathbb{N}$, if for every distinct $x_1, \ldots, x_\ell \in \{0,1\}^n$ and every $y_1, \ldots, y_\ell \in \{0,1\}^m$, it holds that $\Pr_{h \leftarrow \mathcal{H}}[h(x_1) = y_1 \wedge \cdots \wedge h(x_\ell) = y_\ell] = 2^{-\ell m}$.

ℓ-times, restricted length, MAC

Construction 8 (ℓ-time MAC)

Let $\mathcal{H} = \{\mathcal{H}_n \colon \{0,1\}^n \mapsto \{0,1\}^n\}$ be an efficient $(\ell + 1)$-wise independent function family.

- $\mathsf{Gen}(1^n)$: outputs $h \leftarrow \mathcal{H}_n$
- $\mathsf{Mac}(h, m) = h(m)$
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Proof: HW

OWF $\Longrightarrow$ existential unforgeable MAC

Construction 10

Same as Construction 8, but uses function $\mathcal{F} = \{\mathcal{F}_n \colon \{0,1\}^n \mapsto \{0,1\}^n\}$ instead of $\mathcal{H}$.

Claim 11

Assuming that $\mathcal{F}$ is a PRF, then Construction 10 is an existential unforgeable MAC.

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Proof: Easy to prove if $\mathcal{F}$ is a family of random functions. Hence, also holds in case $\mathcal{F}$ is a PRF.$\square$

Collision Resistant Hash Family

Definition 12 (collision resistant hash family (CRH))

A function family $\mathcal{H} = \{\mathcal{H}_n \colon \{0,1\}^* \mapsto \{0,1\}^n\}$ is collision resistant, if

$$\Pr[h \leftarrow \mathcal{H}_n, (x, x') \leftarrow \mathsf{A}(1^n, h) \colon x \neq x' \in \{0,1\}^* \\ \wedge h(x) = h(x')] = \operatorname{neg}(n)$$

for any PPT A.

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for any PPT A.

- Not known to be implied by OWF

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Construction 13 (Length restricted MAC $\implies$ MAC)

Let $(\mathsf{Gen}, \mathsf{Mac}, \mathsf{Vrfy})$ be a length-restricted MAC, and let $\mathcal{H} = \{\mathcal{H}_n \colon \{0,1\}^* \mapsto \{0,1\}^n\}$ be an efficient function family.

- $\mathsf{Gen}'(1^n)$: $k \leftarrow \mathsf{Gen}(1^n)$, $h \leftarrow \mathcal{H}_n$. Set $k' = (k, h)$
- $\mathsf{Mac}'_{k,h}(m) = \mathsf{Mac}_k(h(m))$
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Claim 14

Assume $\mathcal{H}$ is an efficient collision-resistant family and (Gen, Mac, Vrfy) is existential unforgeable, then $(\mathrm{Gen}', \mathrm{Mac}', \mathrm{Vrfy}')$ is existential unforgeable MAC.

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Claim 14

Assume $\mathcal{H}$ is an efficient collision-resistant family and (Gen, Mac, Vrfy) is existential unforgeable, then (Gen′, Mac′, Vrfy′) is existential unforgeable MAC.

Proof: ?

Section 3

Signature Schemes

Definition

Definition 15 (Signature schemes)

A trippet of PPT's (Gen, Sign, Vrfy) such that

1. $\mathsf{Gen}(1^n)$ outputs a pair of keys $(s, v) \in \{0,1\}^* \times \{0,1\}^*$
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A signature scheme is existential unforgeable (EU), if for any oracle-aided PPT A

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Theorem 17

OWFs imply strong existential unforgeable signatures.

Section 4

OWFs $\implies$ Signatures

Length-restricted Signatures

Definition 18 (Length-restricted Signatures)

Same as in Definition 15, but for $(s, v) \in \text{Supp}(G(1^n))$, Sign_s and Vrfy_v only accept messages of length n.

Bounded-query Signatures

Definition 19 (ℓ-time signatures)

A signature scheme is existential unforgeable against ℓ-query (for short, ℓ-time signature), if it is existential unforgeable as in Definition 16, but A can only ask for ℓ queries.

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Claim 20

Assuming CRH exists: length restricted, one-time signatures, imply one-time signatures.

OWF $\Longrightarrow$ length restricted, One Time Signature

Construction 21 (length restricted, one time signature)

Let $f\colon \{0,1\}^n \mapsto \{0,1\}^n$.

1. $\mathrm{Gen}(1^n)$: $s_1^0, s_1^1, \ldots, s_n^0, s_n^1 \leftarrow \{0,1\}^n$, let $s = (s_1^0, s_1^1, \ldots, s_n^0, s_n^1)$ and $v = (v_1^0 = f(s_1^0), v_1^1 = f(s_1^1), \ldots, v_n^0 = f(s_n^0), v_n^1 = f(s_n^1))$
2. $\mathrm{Sign}(s, m)$: Output $(s_1^{m_1}, \ldots, s_n^{m_n})$
3. $\mathrm{Vrfy}(v, m, \sigma = (\sigma_1, \ldots, \sigma_n))$ check that $f(\sigma_i) = v_{m_i}$ for all $i \in [n]$

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2. $\text{Sign}(s, m)$: Output $(s_1^{m_1}, \ldots, s_n^{m_n})$
3. $\text{Vrfy}(v, m, \sigma = (\sigma_1, \ldots, \sigma_n))$ check that $f(\sigma_i) = v_{m_i}$ for all $i \in [n]$

Lemma 22

Assume that f is a OWF, then scheme from Construction 21 is a length restricted one-time signature scheme

Proving Lemma 22

Let a PPT A, $\mathcal{I} \subseteq \mathbb{N}$ and $p \in$ poly that break the security of Construction 21, we use A to invert f.

Algorithm 23 (Inv)

Input: $y \in \{0,1\}^n$

1. Choose $(s, v) \leftarrow Gen(1^n)$ and replace $v_{j^*}^{i^*}$ for a random $i^* \in [n]$ and $j^* \in \{0,1\}$, with y.
2. If $A(1^n, v)$ asks to sign message $m \in \{0,1\}^n$ with $m_{i^*} = j^*$ abort, otherwise use s to answer the query.
3. Let (m, σ) be A's output. If σ is not a valid signature for m, or $m_{i^*} \neq j^*$, abort.
   Otherwise, return σ_{i^*}.

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   Otherwise, return σ_{i^*}.

v is distributed as it is in the real "signature game" (ind. of i^* and j^*). Therefore Inv inverts f w.p. $\frac{1}{2np(n)}$ for any $n \in \mathcal{I}$.

Stateful schemes (also known as, Memory-dependant schemes)

Definition 24 (Stateful scheme)

Same as in Definition 15, but Sign might keep state.

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- Make sense in many applications (e.g., , smartcards)
- We'll use it a building block for building a stateless scheme

Naive construction

Let $(\mathrm{Gen}, \mathrm{Sign}, \mathrm{Vrfy})$ be a one-time signature scheme.

Construction 25 (Naive construction)

1. $\mathrm{Gen}'(1^n)$ outputs $(s_1, v_1) = \mathrm{Gen}(1^n)$.
2. $\mathrm{Sign}_s(m_i)$, where m_i is i'th message to sign: Let $((m_1, \sigma'_1), \ldots, (m_{i-1}, \sigma'_{i-1}))$ be the previously signed pairs of messages/signatures.
   1. Let $(s_{i+1}, v_{i+1}) \leftarrow \mathrm{Gen}(1^n)$
   2. Let $\sigma_i = \mathrm{Sign}_{s_{i-1}}(m_i, v_{i+1})$, and output $\sigma'_i = (\sigma'_{i-1}, m_i, v_{i+1}, \sigma_i)$.
3. $\mathrm{Vrfy}'_v(m, \sigma' = (m_1, v_2, \sigma_1), \ldots, (m_i, v_{i+1}, \sigma_i))$:
   1. Verify $\mathrm{Vrfy}_{v_{j-1}}((m_j, v_{j+1}), \sigma_j) = 1$ for every $j \in [i]$
   2. Verify $m_i = m$

1. State is used for maintaining the private key (e.g., s_i') and to prevent using the same one-time signature twice.
2. Inefficient scheme, thought still polynomial, both running time and signature size are linear in number of signatures

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2. Inefficient scheme, thought still polynomial, both running time and signature size are linear in number of signatures
3. Critically uses the fact that $(\mathrm{Gen}, \mathrm{Sign}, \mathrm{Vrfy})$ is works for any length

Lemma 26

Assume that $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ *is one time signature scheme, then* $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$ *is a stateful existential unforgeable signature scheme.*

Lemma 26

Assume that $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ *is one time signature scheme, then* $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$ *is a stateful existential unforgeable signature scheme.*

Proof: Let a PPT A', $\mathcal{I} \subseteq \mathbb{N}$ and $p \in \mathrm{poly}$ that breaks the security of $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$, we present a PPT A that breaks the security of $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$.

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- We assume for simplicity that p also bounds the query complexity of A'

Proving Lemma 26 cont.

Let the random variables
$(m, \sigma = (m_1, v_2, \sigma_1), \ldots, (m_q, v_{q+1}, \sigma_q))$ be the pair output by A′

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Claim 27

Whenever A′ succeeds, $\exists \widetilde{i} = \widetilde{i}(m, \sigma) \in [q]$ such that:

1. Sign′ *was not* asked by A′ on $m_{\widetilde{i}}$.
2. Sign′ *was* asked by A′ on m_i, for every $i \in [\widetilde{i} - 1]$

Proving Lemma 26 cont.

Let the random variables
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Whenever A$'$ succeeds, $\exists \widetilde{i} = \widetilde{i}(m, \sigma) \in [q]$ such that:

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Proof: Let $\widetilde{i}$ be the maximal index such that condition (2) holds (cannot be $q + 1$).$\square$

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- Let $\widetilde{m} = (m_{\widetilde{i}}, v_{\widetilde{i}+1})$, and let $s_{\widetilde{i}}$ be the signing key generated together with $v_{\widetilde{i}}$.

Proving Lemma 26 cont.

Let the random variables
$(m, \sigma = (m_1, v_2, \sigma_1), \ldots, (m_q, v_{q+1}, \sigma_q))$ be the pair output by A′

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Whenever A′ succeeds, $\exists \widetilde{i} = \widetilde{i}(m, \sigma) \in [q]$ such that:

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Proof: Let $\widetilde{i}$ be the maximal index such that condition (2) holds (cannot be $q + 1$).$\square$

- Let $\widetilde{m} = (m_{\widetilde{i}}, v_{\widetilde{i}+1})$, and let $s_{\widetilde{i}}$ be the signing key generated together with $v_{\widetilde{i}}$.
- Hence, $\mathrm{Sign}_{s_{\widetilde{i}}}(\sigma_{\widetilde{i}}, \widetilde{m}) = 1$, and Sign_{s_i} was not queried by Sign'_s on $\widetilde{m}$.

Definition of A

Algorithm 28 (A)

Input: v, 1^n
Oracle: Sign_s

1. Choose $i^* \leftarrow [p = p(n)]$ and $(s', v') \leftarrow \mathrm{Gen}'(1^n)$.
2. Emulate a random execution of $\mathrm{A}'^{\mathrm{Sign}'_{s'}}$ with a single twist:
   - On the i^*'th call to $\mathrm{Sign}'_{s'}$, set $v_{i^*} = v$ (rather then choosing it via Gen)
   - When need to sign using s_{i^*}, use Sign_s.
3. Let $(m, \sigma = (m_1, v_1, \sigma_1), \ldots, (m_q, v_q, \sigma_q)) \leftarrow \mathrm{A}'$
4. Output $((m_{i^*}, v_{i^*}), \sigma_{i^*})$ (abort if $i^* > q$))

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3. Let $(m, \sigma = (m_1, v_1, \sigma_1), \ldots, (m_q, v_q, \sigma_q)) \leftarrow \mathsf{A}'$
4. Output $((m_{i^*}, v_{i^*}), \sigma_{i^*})$ (abort if $i^* > q$))

- Sign_s is called at most once

Definition of A

Algorithm 28 (A)

Input: v, 1^n

Oracle: Sign_s

1. Choose $i^* \leftarrow [p = p(n)]$ and $(s', v') \leftarrow \mathrm{Gen}'(1^n)$.
2. Emulate a random execution of $\mathrm{A}'^{\mathrm{Sign}'_{s'}}$ with a single twist:
   - On the i^*'th call to $\mathrm{Sign}'_{s'}$, set $v_{i^*} = v$ (rather then choosing it via Gen)
   - When need to sign using s_{i^*}, use Sign_s.
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- Sign_s is called at most once
- The emulated game $\mathsf{A}'^{\text{Sign}'_{s'}}$ has the “right" distribution.
- A breaks (Gen, Sign, Vrfy) whenever $i^* = \widetilde{i} > 1$.

Analysis of A

For any $n \in \mathcal{I}$

$$
\begin{aligned}
&\Pr[\mathsf{A}(1^n) \text{ breaks } (\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})] \\
&\quad \geq \quad \Pr_{i* \leftarrow [p = p(n)]}[i = \widetilde{i}] \\
&\quad \geq \quad \frac{1}{p} \cdot \Pr[\mathsf{A}' \text{ breaks } (\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')] \geq \frac{1}{p(n)^2}
\end{aligned}
$$

"Somewhat"-Stateful Schemes

A one-time scheme (Gen, Sign, Vrfy), and $\ell = \ell(n) \in \omega(\log n)$

Construction 29

- $\mathrm{Gen}'(1^n)$: output $(s_\lambda, v_\lambda) \leftarrow \mathrm{Gen}(1^n)$.
- $\mathrm{Sign}'_s(m)$: choose *unused* $\bar{r} \in \{0,1\}^\ell$
  1. For $i = 0$ to $\ell - 1$: if $a_{\bar{r}_{1,\ldots,i}}$ was not set:
     1. For both $j \in \{0,1\}$, let $(s_{\bar{r}_{1,\ldots,i},j}, v_{\bar{r}_{1,\ldots,i},j}) \leftarrow \mathrm{Gen}(1^n)$
     2. $\sigma_{\bar{r}_{1,\ldots,i}} = \mathrm{Sign}_{s_{\bar{r}_{1,\ldots,i}}}(a_{1,\ldots,i} = (v_{\bar{r}_{1,\ldots,i},0}, v_{\bar{r}_{1,\ldots,i},1}))$
  2. Output $(\bar{r}, a_\lambda, \sigma_\lambda, \ldots, a_{\bar{r}_{1,\ldots,\ell-1}}, \sigma_{\bar{r}_{1,\ldots,\ell-1}}, \sigma_{\bar{r}} = \mathrm{Sign}_{s_{\bar{r}}}(m))$
- $\mathrm{Vrfy}'_v(m, \sigma' = (\bar{r}, a_\lambda, \sigma_\lambda, \ldots, a_{\bar{r}-1}, \sigma_{\bar{r}_{1,\ldots,\ell-1}}, \sigma_{\bar{r}})$
  1. Verify $\mathrm{Vrfy}_{v_{\bar{r}_{1,\ldots,i}}}(a_{\bar{r}_{1,\ldots,i}}, \sigma_{\bar{r}_{1,\ldots,i}}) = 1$ for every $i \in \{0, \ldots, \ell - 1\}$
  2. Verify $\mathrm{Vrfy}_{v_{\bar{r}}}(m, \sigma_{\bar{r}}) = 1$ (where $v_{\bar{r}} = (a_{\bar{r}})_{\bar{r}[\ell]}$)

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3. Each leaf is visited at most once.
4. Each one-time signature is used once.

Lemma 30

Assume that $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ *is one time signature scheme, then* $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$ *is a stateful existential unforgeable signature scheme.*

Proof:

Lemma 30

Assume that $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ *is one time signature scheme, then* $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$ *is a stateful existential unforgeable signature scheme.*

Proof: Let $(m, \sigma' = (\bar{r}, a_\lambda, \sigma_\lambda, \ldots, a_{\bar{r}-1}, \sigma_{\bar{r}_{1,\ldots,\ell-1}}, \sigma_{\bar{r}})$ be the output of a cheating A' and let $a_{\bar{r}} = m$

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Claim 31

Whenever A$'$ succeeds, $\exists \widetilde{i} = \widetilde{i}(m, \sigma') \in \{0, \ldots, \ell\}$ such that:

1. Sign$'_s$ queried $\mathrm{Sign}_{s_{\overline{r}_{1,\ldots,i}}}(a_{\overline{r}_{1,\ldots,i}})$ for every $i \in [\widetilde{i} - 1]$, where $s_{\overline{r}_{1,\ldots,i}}$ is the value sampled by Sign$'$ when sampling $a_{\overline{r}_{1,\ldots,i-1}}$ (or s_λ, if $\widetilde{i} = 0$)
2. Sign$'_s$ did not query $\mathrm{Sign}_{s_{\overline{r}_{1,\ldots,i}}}(a_{\overline{r}_{1,\ldots,i}})$.

Stateless Scheme

Inefficient scheme:

Let $\Pi_{\ell,q}$ be the set of random functions from $\{0,1\}^*$ to $\{0,1\}^q$.

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2. $\mathsf{Sign}'(1^n)$:
   1. choose $\bar{r} = \pi(0^\ell \circ m)_{1,\dots,\ell}$
   2. When setting $(s_{\bar{r}_{1,\dots,i},j}, v_{\bar{r}_{1,\dots,i},j}) \leftarrow \mathsf{Gen}(1^n)$, use $\pi(\bar{r}_{1,\dots,i},j)$ as the randomness for Gen.

- Sign' keeps no state
- A single one-time signature key might be used several times, but always on *the same* message

Efficient scheme: use PRF

Without CRH

Definition 32 (target collision resistant (TCR))

A function family $\mathcal{H} = \{\mathcal{H}_n\}$ is target collision resistant, if any pair of PPT's $\mathsf{A}_1, \mathsf{A}_2$:

$$\Pr[(x, a) \leftarrow \mathsf{A}_1(1^n); h \leftarrow \mathcal{H}_n; x' \leftarrow \mathsf{A}_2(a, h) : x \neq x' \wedge h(x) = h(x')] = \operatorname{neg}(n)$$

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Theorem 33

OWFs imply efficient compressing TCRs.

Definition 34 (target one-time signatures)

A signature scheme (Gen, Sign, Vrfy) is target one-time existential unforgeable (for short, target one-time signature), if for any pair of PPT's A_1, A_2

$$\begin{aligned}&\Pr\big[(m,a) \leftarrow A_1(1^n); (s,v) \leftarrow \mathrm{Gen}(1^n);\\ &\quad (m',\sigma) \leftarrow A(a, \mathrm{Sign}_s(m)) \colon m' \neq m \wedge \mathrm{Vrfy}_v(m',\sigma) = 1\big]\\ &\quad = \mathrm{neg}(n)\end{aligned}$$

Definition 34 (target one-time signatures)

A signature scheme $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ is target one-time existential unforgeable (for short, target one-time signature), if for any pair of PPT's $\mathsf{A}_1, \mathsf{A}_2$

$$\begin{aligned}&\Pr\big[(m,a) \leftarrow \mathsf{A}_1(1^n); (s,v) \leftarrow \mathsf{Gen}(1^n);\\&\quad (m',\sigma) \leftarrow \mathsf{A}(a, \mathsf{Sign}_s(m)) \colon m' \neq m \wedge \mathsf{Vrfy}_v(m',\sigma) = 1\big]\\&\quad = \mathsf{neg}(n)\end{aligned}$$

Claim 35

OWFs imply target one-time signatures.

Definition 36 (random one-time signatures)

A signature scheme $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ is random one-time existential unforgeable (for short, random one-time signature), if for any PPT A and any samplable ensemble $\mathcal{M} = \{\mathcal{M}_n\}_{n \in \mathbb{N}}$, it holds that

$$\Pr\Big[m \leftarrow \mathcal{M}_n; (s, v) \leftarrow \mathsf{Gen}(1^n); (m', \sigma) \leftarrow \mathsf{A}(m, \mathsf{Sign}_s(m)) :\\ m' \neq m \wedge \mathsf{Vrfy}_v(m', \sigma) = 1\Big]\\ = \operatorname{neg}(n)$$

Definition 36 (random one-time signatures)

A signature scheme (Gen, Sign, Vrfy) is random one-time existential unforgeable (for short, random one-time signature), if for any PPT A and any samplable ensemble $\mathcal{M} = \{\mathcal{M}_n\}_{n\in\mathbb{N}}$, it holds that

$$\Pr\left[m \leftarrow \mathcal{M}_n; (s, v) \leftarrow \mathrm{Gen}(1^n); (m', \sigma) \leftarrow \mathrm{A}(m, \mathrm{Sign}_s(m)) : m' \neq m \wedge \mathrm{Vrfy}_v(m', \sigma) = 1\right] = \mathrm{neg}(n)$$

Claim 37

Assume (Gen, Sign, Vrfy) is target one-time existential unforgeable, then it is random one-time existential unforgeable.

Lemma 38

Assume that $(\mathrm{Gen}, \mathrm{Sign}, \mathrm{Vrfy})$ *is a target one-time signature scheme, then* $(\mathrm{Gen}', \mathrm{Sign}', \mathrm{Vrfy}')$ *from Construction 29 is a stateful existential unforgeable signature scheme.*

Lemma 38

Assume that (Gen, Sign, Vrfy) *is a target one-time signature scheme, then* (Gen′, Sign′, Vrfy′) *from Construction 29 is a stateful existential unforgeable signature scheme.*

Proof: ?